

AN-240 Wide-Range Current-to-Frequency Converters

ABSTRACT

This application report discusses a wide-range current-to-frequency converters.

Does an analog-to-digital converter cost you a lot if you need many bits of accuracy and dynamic range? Absolute accuracy better than 0.1% is likely to be expensive. But a capability for wide dynamic range can be quite inexpensive. Voltage-to-frequency (V-to-F) converters are becoming popular as a low-cost form of A-to-D conversion because they can handle a wide dynamic range of signals with good accuracy.

Most voltage-to-frequency (V-to-F) converters actually operate with an input current which is proportional to the voltage input:

$$I_{IN} = \frac{V_{IN}}{R_{IN}} \quad (1)$$

(Figure 1). This current is integrated by an op amp, and a charge dispenser acts as the feedback path, to balance out the average input current. When an amount of charge $Q=I \cdot T$ (or $Q=C \cdot V$) per cycle is dispensed by the circuit, then the frequency will be:

$$f = \left(\frac{V_{IN} - V_{OS}}{R_{IN}} + I_b \right) \times \frac{1}{Q} \quad (2)$$

When V_{IN} is large:

$$f \approx \frac{V_{IN}}{R_{IN}} \times \frac{1}{Q} \quad (3)$$

When V_{IN} covers a wide dynamic range, the V_{OS} and I_b of the op amp must be considered, as they greatly affect the usable accuracy when the input signal is very small. For example, when the full-scale input is 10V, a signal which is 100 dB below full-scale will be only 100 μ V. If the op amp has an offset drift of $\pm 100 \mu$ V, (whether caused by time or temperature), that would cause a $\pm 100\%$ error at this signal level. However, a current-to-frequency converter can easily cover a 120 dB range because the voltage offset problem is not significant when the input signal is actually a current source. Let's study the architecture and design of a current-to-frequency converter, to see where we can take advantage of this.

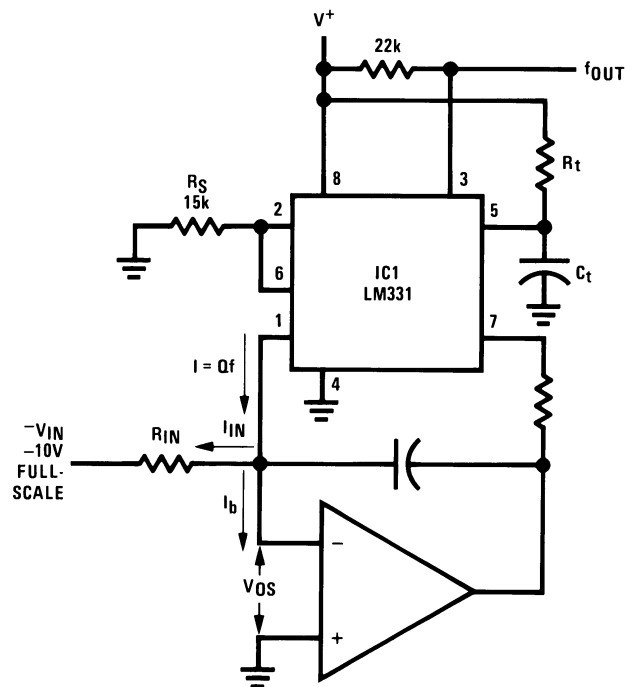


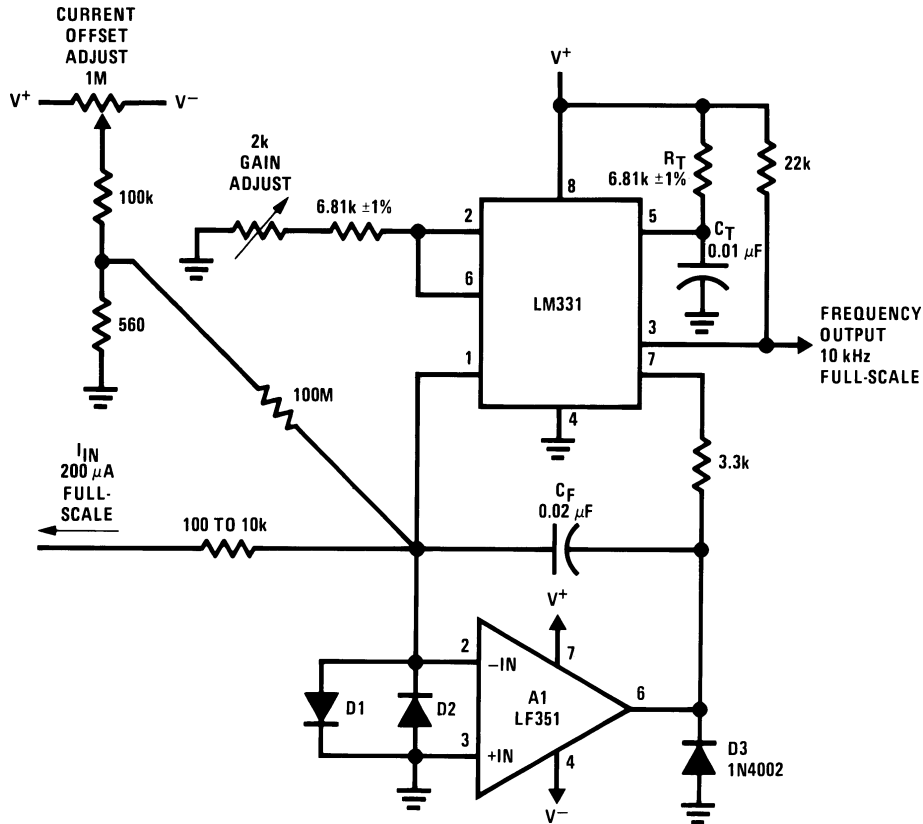
Figure 1. Typical Voltage-to-Frequency Converter

When the input signal is a current, the use of a low-voltage-drift op amp becomes of no advantage, and low bias current is the prime specification. A low-cost BI-FET™ op amp such as the LF351A has $I_b < 100$ pA, and temperature coefficient of I_b less than 10 pA/°C, at room temperature. In a typical circuit such as [Figure 2](#), the leakage of the charge dispenser is important, too. The LM331 is only specified at 10 nA max at room temperature, because that is the smallest current which can be measured economically on high-speed test equipment. The leakage of the LM331's current-source output at pin 1 is usually 2 pA to 4 pA, and is always less than the 100 pA mentioned above, at 25°C .

The feedback capacitor C_F should be of a low-leakage type, such as polypropylene or polystyrene. (At any temperature above 35°C , mylar's leakage may be excessive.) Also, low-leakage diodes are recommended to protect the circuit's input from any possible fault conditions at the input. (A 1N914 may leak 100 pA even with only 1 millivolt across it, and is unsuitable.)

After trimming this circuit for a low offset when I_{IN} is 1 nA, the circuit will operate with an input range of 120 dB, from 200 μA to 100 pA, and an accuracy or linearity error well below (0.02% of the signal plus 0.0001% of full-scale).

The zero-offset drift will be below 5 or 10 pA/°C, so when the input is 100 dB down from full-scale, the zero drift will be less than 2% of signal, for a $\pm 5^\circ\text{C}$ temperature range. Another way of indicating this performance is to realize that when the input is $1/1000$ of full-scale, zero drift will be less than 1% of that small signal, for a 0°C to 70°C temperature range.



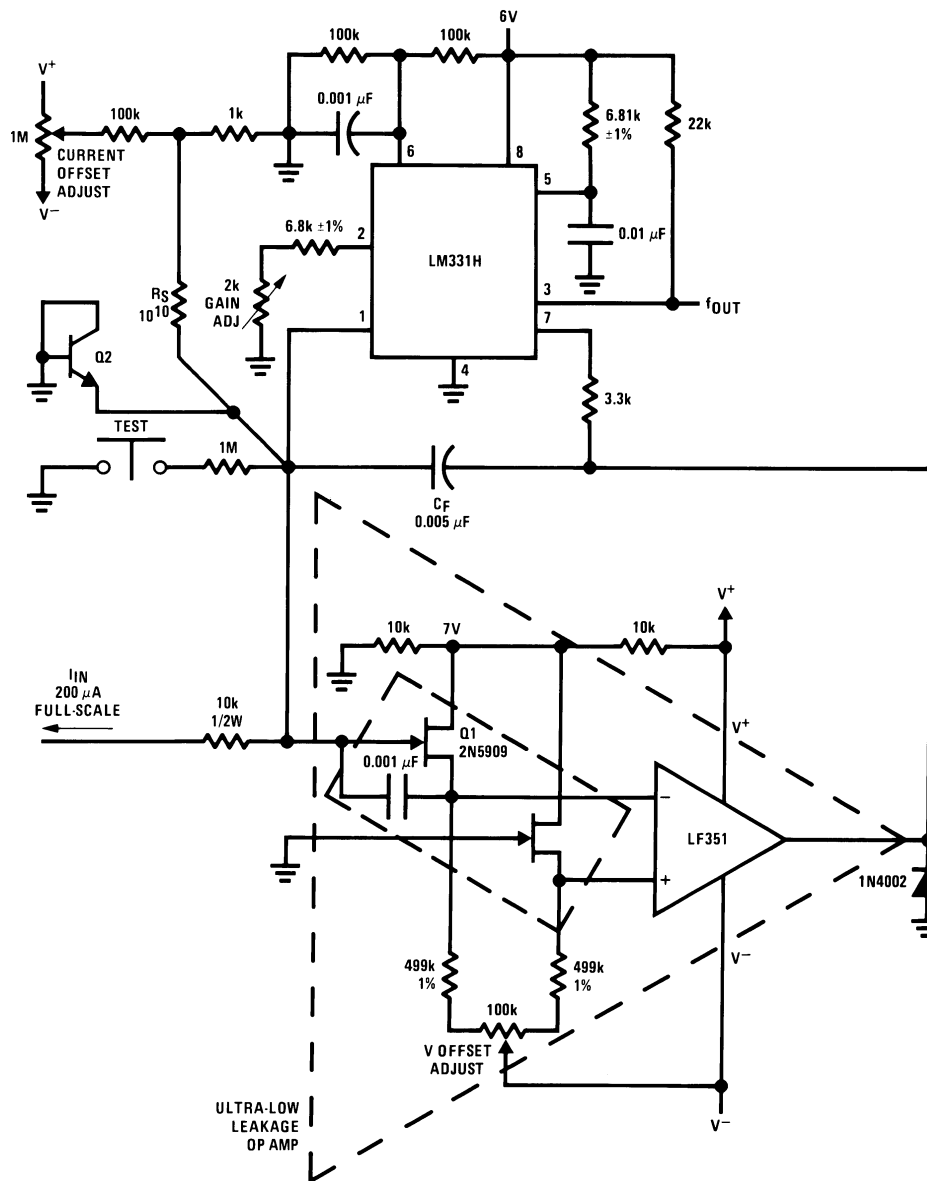
D1, D2=1N457, 1N484, or similar low-leakage planar diode

Figure 2. Practical Wide-Range Current-to-Frequency Converter

What if this isn't good enough? You *could* get a better op amp. For example, an LH0022C has 10 pA max I_b . But it is silly to pay for such a good op amp, with low V offset errors, when only a low input current specification is needed. The circuit of [Figure 3](#) shows the simple scheme of using FET followers ahead of a conventional op amp. An LF351 type is suitable because it is a cheap, quick amplifier, well suited for this work. The 2N5909s have a maximum I_b of 1.0 pA, and at room temperature it will drift only 0.1 pA/°C. Typical drift is 0.02 pA/°C.

The voltage offset adjust pot is used to bring the summing point within a millivolt of ground. With an input signal big enough to cause $f_{OUT}=1$ second per cycle, trim the V offset adjust pot so that closing the *test* switch makes no effect on the output frequency (or, output period). Then adjust the input current offset pot, to get $f_{OUT}=1/1000$ of full-scale when I_{IN} is 1/1000 of full-scale. When I_{IN} covers the 140 dB range, from 200 μ A to 20 pA, the output will be stable, with very good zero offset stability, for a limited temperature range around room temperature. Note these precautions and special procedures:

1. Run the LM331 on 5V to 6V to keep leakage down and to cut the dissipation and temperature rise, too.
2. Run the FETs with a 6V drain supply.
3. Guard all summing point wiring away from all other voltages.



Q1 - 2N5909 or similar
 $1G < 1 \text{ pA}$
 Q2 - 2N930 or 2N3565

Figure 3. Very-Wide-Range Current-to-Frequency Converter

An alternate approach, shown in [Figure 4](#), uses an LM11C as the input pre-amplifier. The LM11C has much better voltage drift than any of the other amplifiers shown here (normally less than $2 \mu\text{V}/^\circ\text{C}$) and excellent current drift, less than $1 \text{ pA}/^\circ\text{C}$ by itself, and typically $0.2 \text{ pA}/^\circ\text{C}$ when trimmed with the 2N3904 bias current compensation circuit as shown. Of course, the LM331's leakage of $1 \text{ pA}/^\circ\text{C}$ will still double every 10°C , so that having an amplifier with excellent I_b characteristics does not solve the whole problem, when trying to get good accuracy with a 100 pA signal. For that job, even the leakage of the LM331 must be guarded out!

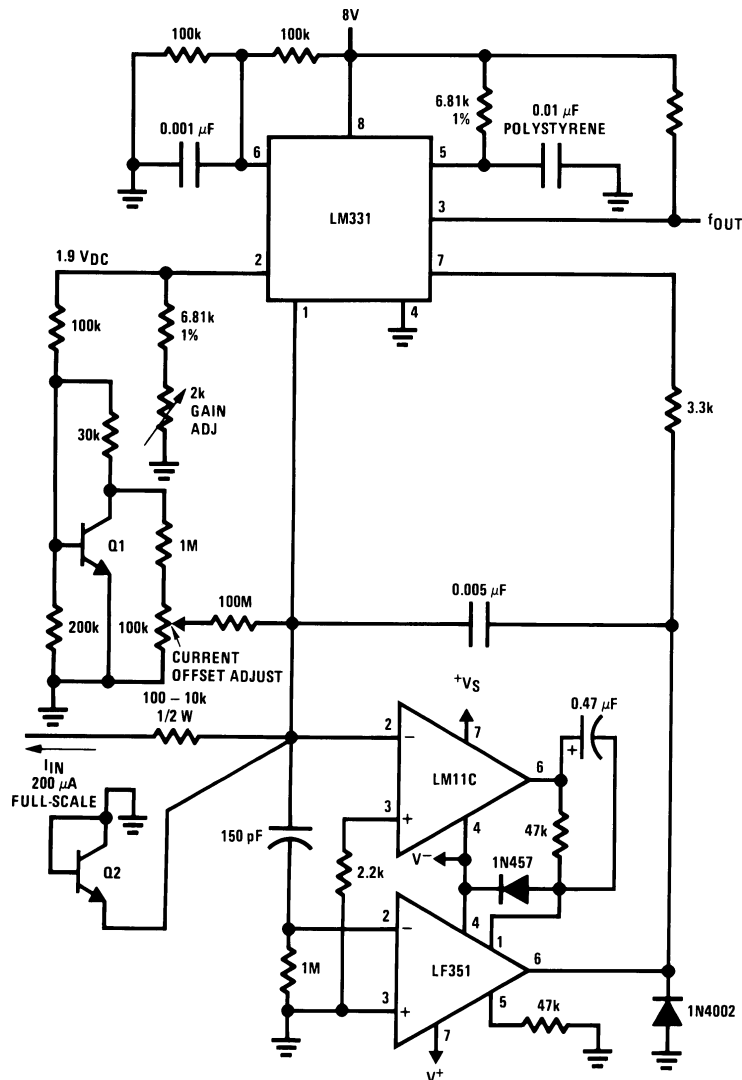
What if even lower ranges of input current must be accepted? While it might be possible to use a current-to-voltage converter ahead of a V-to-F converter, offset voltage drifts would hurt dynamic range badly. Response and zero-drift of such an I-V will be disappointing. Also, it is not feasible to starve the LM331 to an arbitrary extent.

For example, while its I_{OUT} (full-scale) of 280 μA DC can be cut to 10 μA or 28 μA , it cannot be cut to 1 μA or 2.8 μA with good accuracy at 10 kHz, because the internal switches in the integrated circuit will not operate with best speed and precision at such low currents.

Instead, the output current from pin 1 of the LM331 can be fed through a current attenuator circuit, as shown in Figure 5. The LM334 (temperature-to-current converter IC) causes -120 mV bias to appear at the base of Q2. When a current flows out of pin 1 of the LM331, 1/100 of the current will flow out of Q1's collector, and the rest will go out of Q2's collector. As the LM334's current is linearly proportional to Kelvin temperature, the -120 mV at Q2's base will change linearly with temperature so that the Q1/Q2 current divider stays at 1:100, invariant of temperature, according to the equation:

$$i_1/i_2 = e^{\frac{q(V_{b1} - V_{b2})}{kT}} \quad (4)$$

This current attenuator will work stably and accurately, even at high speeds, such as for 4 μs current pulses. Thus, the output of Q1 is a charge pump which puts out only 10 picocoulombs per pulse, with surprisingly good accuracy. Note also that the LM331's leakage is substantially attenuated also, by a factor of 100 or more, so that source of error virtually disappears. When Q1 is off, it is really OFF, and its leakage is typically 0.01 pA if the summing point is within a millivolt or two of ground.



Q1, 2N3904 or any silicon NPN
 Q2, 2N930 or 2N3565

Figure 4. Very-Wide-Range I-to-F Converter with Low Voltage Drift

To do justice to this low leakage of the VFC, the op amp should be made with MOSFETs for Q3 and Q4, such as the Intersil 3N165 or 3N190 dual MOSFET (with no gate-protection diodes). When MOSFETs have relatively poor offset voltage, offset voltage drift, and voltage noise, this circuit does not care much about these characteristics, but instead takes advantage of the MOSFET's superior current leakage and current drift.

Now, with an input current of 1 μA , the full-scale output frequency will be 100 kHz. At a 1 nA input, the output frequency will be 100 Hz. And, when the input current is 1 pA, the output frequency will drop to 1 cycle per 10 seconds or 100 mHz. When the input current drops to zero, frequencies as small as 500 μHz have been observed, at 25°C and also as warm as 35°C. Here is a wide-range data converter whose zero drift is well below 1 ppm per 10°C! (Rather more like 0.001 ppm per °C.) The usable dynamic range is better than 140 dB, with excellent accuracy at inputs between 100% and 1% and 0.01% and 0.0001% of full-scale.

If a positive signal is of interest, the LM331 can be applied with a current reflector as in [Figure 6](#). This current reflector has high output impedance, and low leakage. Its output can go directly to the summing point, or via a current attenuator made with NPN transistors, similar to the PNP circuit of [Figure 5](#). This circuit has been observed to cover a wide (130 dB) range, with 0.1% of signal accuracy.

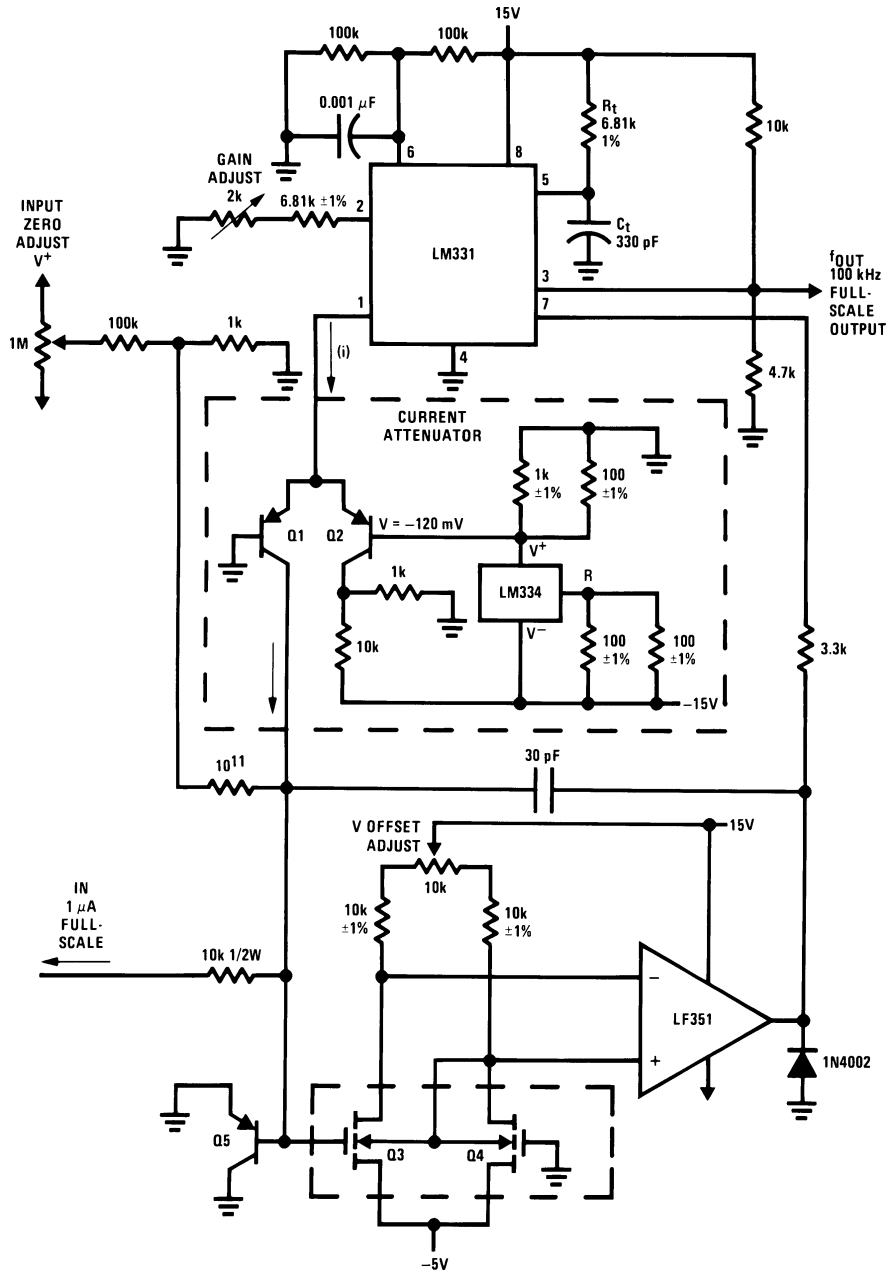
What is the significance of this wide-range current-to-frequency converter? In many industrial systems the question of using an inexpensive 8-bit converter instead of an expensive 12-bit data converter is a battle which is decided everyday. But if the signal source is actually a current source, then you can use a V-to-F converter to make a cheap 14-bit converter or an inexpensive converter with 18 bits of dynamic range. The choice is yours.

Why use an I-to-F converter?

- It is a natural form of A-to-D conversion.
- It naturally facilitates integration, as well.
- There are many signals in the world, such as photospectrometer currents, which like to be digitized and integrated as a standard part of the analysis of the data.
- Similarly: photocurrents, dosimeters, ionization currents, are examples of currents which beg to be integrated in a current-to-frequency meter.
- Other signal sources which provide output currents are:
 - Phototransistors
 - Photo diodes
 - Photoresistors (with a fixed voltage bias)
 - Photomultiplier tubes
 - Some temperature sensors
 - Some IC signal conditioners

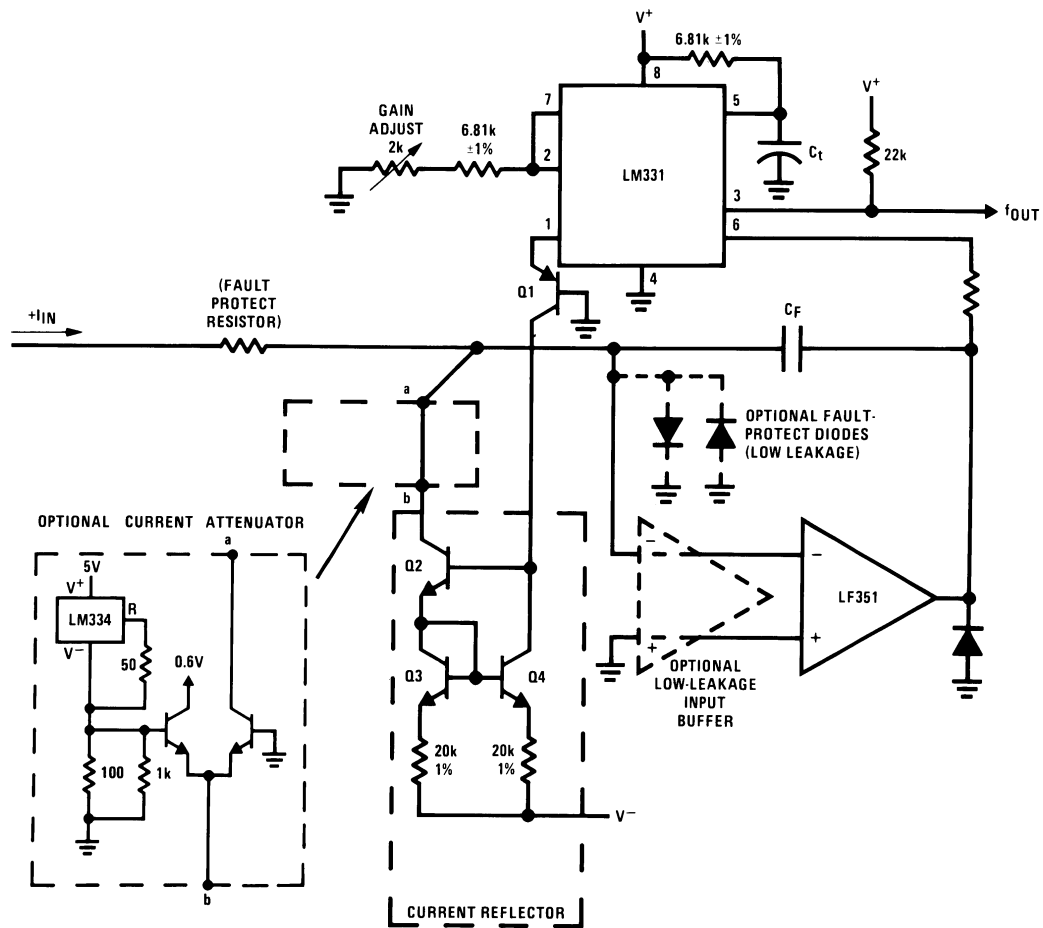
Why have a fast frequency out?

- A 100 kHz output full-scale frequency instead of 10 kHz means that you have 10 times the resolution of the signal. For example, when I_{IN} is 0.01% of full-scale, the f will be 10 Hz. If you integrate or count that frequency for just 10 seconds, you can resolve the signal to within 1% – a factor of 10 better than if the full-scale frequency were slower.



Q1, Q2, Q5 - 2N3906, 2N4250 or similar
 Q3, Q4 - 3N165, 3N190 or similar. See text
 Keep Q1, Q2 and LM334 at the same temperature

Figure 5. Picoampere-to-Frequency Converters



Q1 - 2N4250 or 2N3906
 Q2, Q3, Q4 - 2N3904 or 2N3565

Figure 6. Current-to-Frequency Converter for Positive Signals

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, enhancements, improvements and other changes to its semiconductor products and services per JESD46, latest issue, and to discontinue any product or service per JESD48, latest issue. Buyers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All semiconductor products (also referred to herein as "components") are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its components to the specifications applicable at the time of sale, in accordance with the warranty in TI's terms and conditions of sale of semiconductor products. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by applicable law, testing of all parameters of each component is not necessarily performed.

TI assumes no liability for applications assistance or the design of Buyers' products. Buyers are responsible for their products and applications using TI components. To minimize the risks associated with Buyers' products and applications, Buyers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any patent right, copyright, mask work right, or other intellectual property right relating to any combination, machine, or process in which TI components or services are used. Information published by TI regarding third-party products or services does not constitute a license to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of significant portions of TI information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. TI is not responsible or liable for such altered documentation. Information of third parties may be subject to additional restrictions.

Resale of TI components or services with statements different from or beyond the parameters stated by TI for that component or service voids all express and any implied warranties for the associated TI component or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Buyer acknowledges and agrees that it is solely responsible for compliance with all legal, regulatory and safety-related requirements concerning its products, and any use of TI components in its applications, notwithstanding any applications-related information or support that may be provided by TI. Buyer represents and agrees that it has all the necessary expertise to create and implement safeguards which anticipate dangerous consequences of failures, monitor failures and their consequences, lessen the likelihood of failures that might cause harm and take appropriate remedial actions. Buyer will fully indemnify TI and its representatives against any damages arising out of the use of any TI components in safety-critical applications.

In some cases, TI components may be promoted specifically to facilitate safety-related applications. With such components, TI's goal is to help enable customers to design and create their own end-product solutions that meet applicable functional safety standards and requirements. Nonetheless, such components are subject to these terms.

No TI components are authorized for use in FDA Class III (or similar life-critical medical equipment) unless authorized officers of the parties have executed a special agreement specifically governing such use.

Only those TI components which TI has specifically designated as military grade or "enhanced plastic" are designed and intended for use in military/aerospace applications or environments. Buyer acknowledges and agrees that any military or aerospace use of TI components which have **not** been so designated is solely at the Buyer's risk, and that Buyer is solely responsible for compliance with all legal and regulatory requirements in connection with such use.

TI has specifically designated certain components as meeting ISO/TS16949 requirements, mainly for automotive use. In any case of use of non-designated products, TI will not be responsible for any failure to meet ISO/TS16949.

Products

Audio	www.ti.com/audio
Amplifiers	amplifier.ti.com
Data Converters	dataconverter.ti.com
DLP® Products	www.dlp.com
DSP	dsp.ti.com
Clocks and Timers	www.ti.com/clocks
Interface	interface.ti.com
Logic	logic.ti.com
Power Mgmt	power.ti.com
Microcontrollers	microcontroller.ti.com
RFID	www.ti-rfid.com
OMAP Applications Processors	www.ti.com/omap
Wireless Connectivity	www.ti.com/wirelessconnectivity

Applications

Automotive and Transportation	www.ti.com/automotive
Communications and Telecom	www.ti.com/communications
Computers and Peripherals	www.ti.com/computers
Consumer Electronics	www.ti.com/consumer-apps
Energy and Lighting	www.ti.com/energy
Industrial	www.ti.com/industrial
Medical	www.ti.com/medical
Security	www.ti.com/security
Space, Avionics and Defense	www.ti.com/space-avionics-defense
Video and Imaging	www.ti.com/video

TI E2E Community

e2e.ti.com